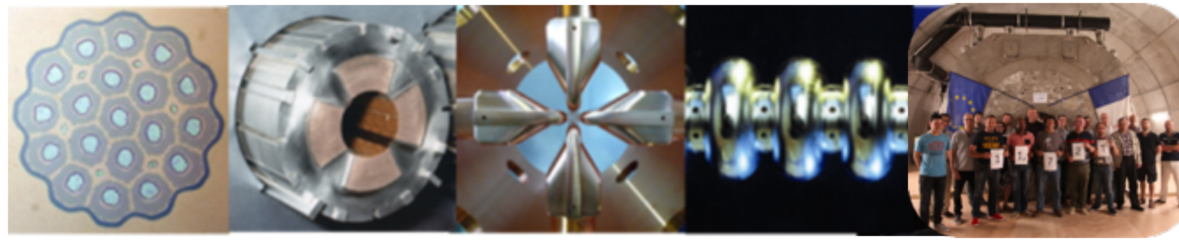
DE LA RECHERCHE À L'INDUSTRIE

Irfu
Institut de recherche sur les lois fondamentales de l'Univers

DACM

www.cea.fr



CEA *PARIS SACLAY*

MAGNET

PERSPECTIVES

Pierre Vedrine

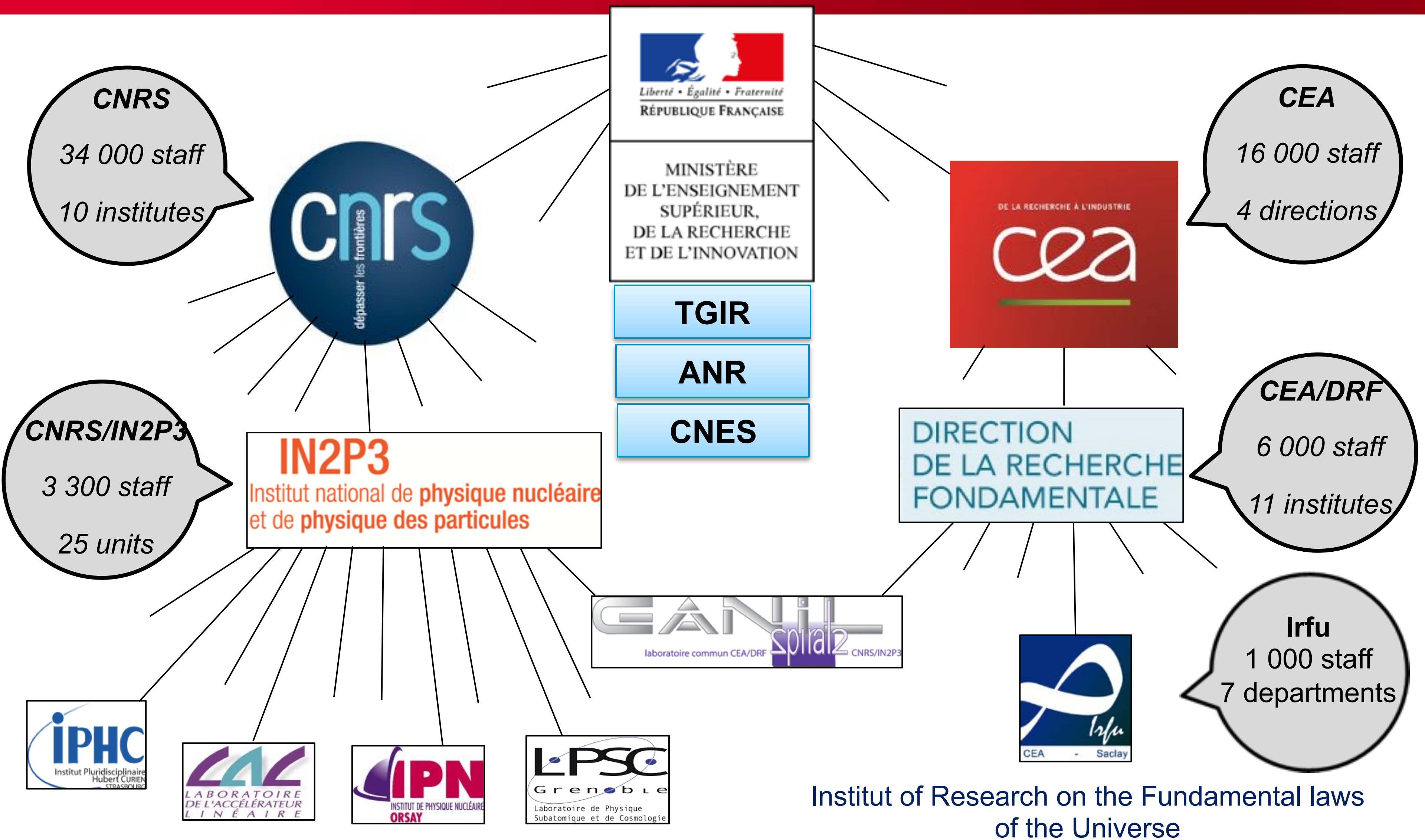
Head of Accelerator, Cryogenics and superconducting Magnet Department

CEA Paris Saclay /DRF/Irfu

Overview of Accelerator and Superconducting Magnet R&D

Paris Saclay

ACCELERATOR R&D IN FRANCE



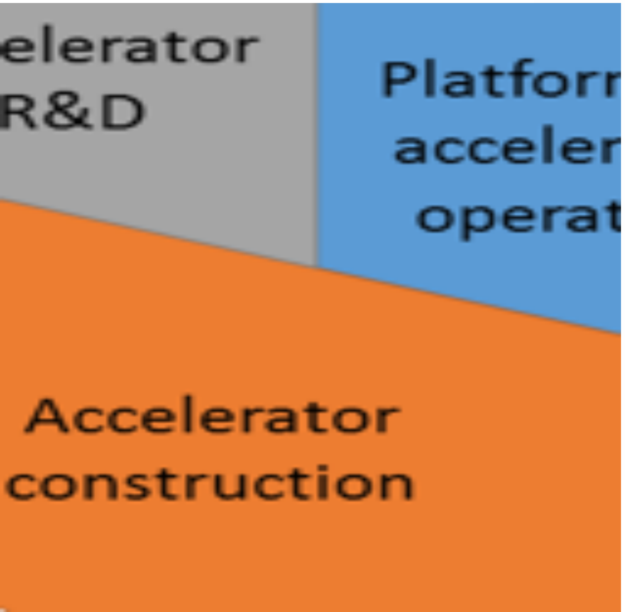
about 300 FTE on accelerators/magnets (incl. GANIL-CNRS) in 13 labs/institutes

about 250 FTE on accelerators/magnets (incl. GANIL-CEA) in 1 institute

ACCELERATOR R&D LABS IN FRANCE

IN2P3 labs

Total of about **550** FTE



+ 2 French « sociétés civiles »

International (21 partners, FR 7.5%)

French (CNRS 72%, CEA 28%)

ACCELERATOR R&D IN FRANCE – MAIN SKILLS

- High-field superconducting magnets
- Superconducting accelerating cavities and cryotechnology
- Sources & injectors
- Radioactive beams
- Beam dynamics, final focus
- Plasma acceleration, laser/beam interactions
- Beam instrumentation
- Related technologies (RF, vacuum…)

ACCELERATOR R&D IN FRANCE – DRIVING FORCES

Push towards
higher energies & higher gradients

- ✓ Superconducting technologies (RF, magnets)
- ✓ Next generation colliders (ILC, CLIC, FCC…)
- ✓ Laser-plasma acceleration

Push towards
higher intensity & luminosity

- ✓ Particle sources and injectors
- ✓ High-current/low emittance beams
- ✓ High-power RF systems

Push towards
higher beam quality & reliability

- ✓ Increase performance & efficiency
- ✓ Increase safety

Make accelerators and magnets
available to societal needs

- ✓ Cancer treatment (hadrontherapy, radioisotope prod.)
- ✓ Application to energy (fusion, ADS)
- ✓ Compact accelerators for light sources, neutron sources , etc…

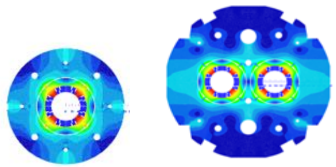
MAGNET PERSPECTIVES AT CEA PARIS SACLAY

NbTi

Accelerator magnets for LHC

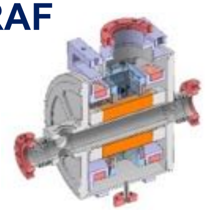
MQ

MQYY

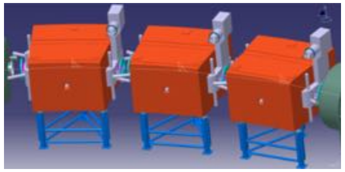


Other Accelerator Magnet

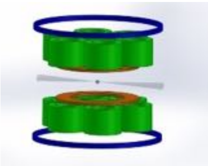
SARAF



SuperFRS



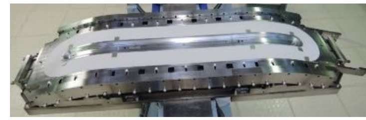
MRI magnet: **ISEULT**



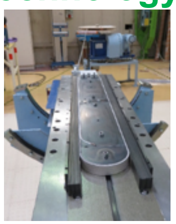
Special magnet
WAVE: neutron diffraction=> condensed matter physics

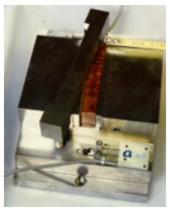
Nb_3Sn

FRESCA 2

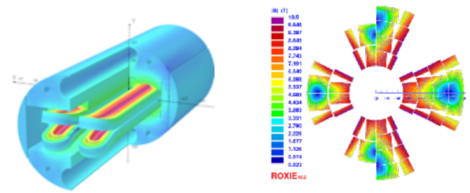


Technology development





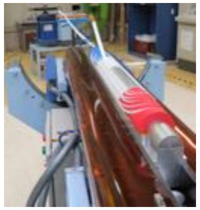
Dipole and Quad for FCC



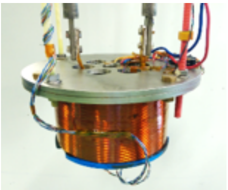
HTS => ReBCO

For accelerator magnets
EUCARD

EUCARD2



For high field magnets



MgB_2

LOTUS: radio isotope production

Conductor characterization

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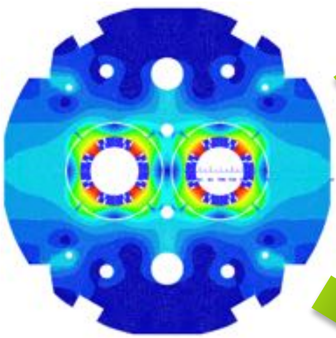
D A C M

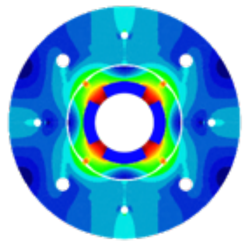
Some examples…

- **Magnets for Accelerators**
- Magnets for Detectors
- High field magnets
- MRI magnets

QUADRUPOLE FOR HILUMI



HL-LHC MQYY

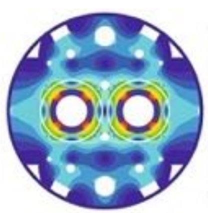


MQYYM

- **Short Model (1.32m) – single aperture**
- Nominal current: 4550 A
- External diameter : 360 mm
- G= 120 T/m ; 90 mm aperture
- NbTi Cable with kapton insulation

HiLumi HL-LHC PROJECT

- Manufacturing of two long prototytpes



QUACO

PHASE 1 Concept. design	PHASE 2 Engineering design	PHASE 3 **MQYYP** Manufacturing

ELYTT ENERGY

SIGMAPHI ACCELERATOR TECHNOLOGIES

HORIZON 2020

Narodowe Centrum Badań Jądrowych National Centre for Nuclear Research ŚWIERK

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

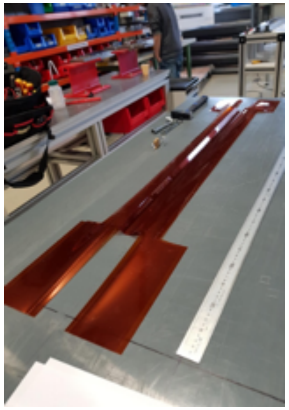
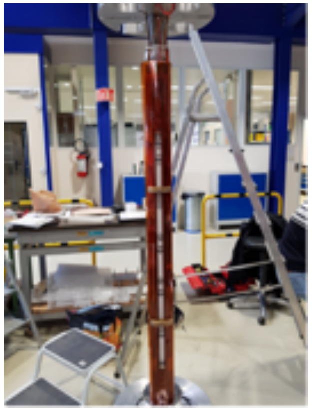
CERN

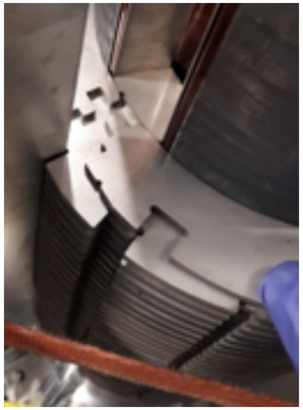
MQYYM WINDING @ SACLAY

- Winding of 10 coils at Saclay



- Assembly at CERN




- **Cold tests at Saclay Winter 2020**

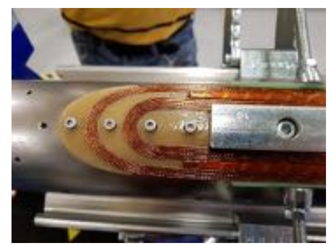
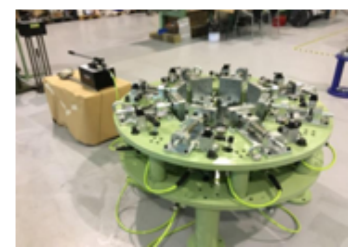
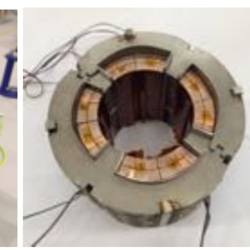
PROTOTYPE WINDING IN INDUSTRY (QUACO)

- Winding of one 4 m long prototype at Sigmaphi and Elytt Energy
- Validation of the mechanical structure is ongoing







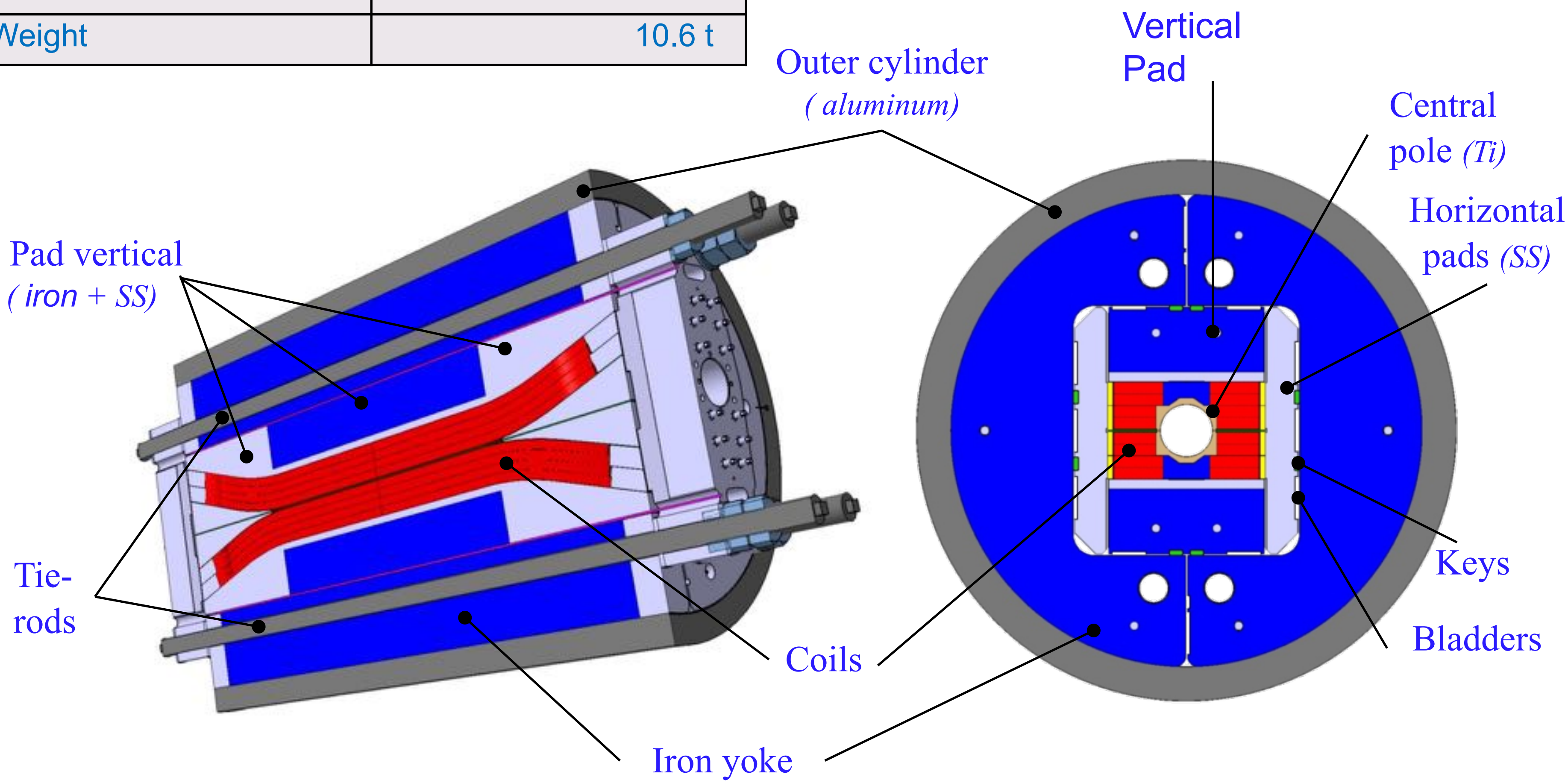
SIGMAPHI ACCELERATOR TECHNOLOGIES

ELYTT ENERGY

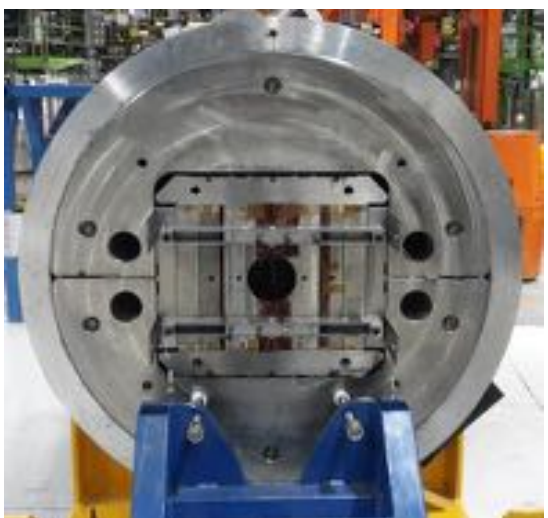
- **Tests of the two prototypes scheduled in septembre 2020 at Saclay**

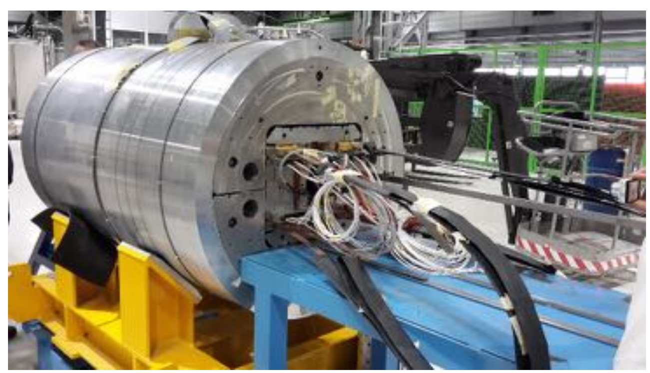
FRESCA 2 (NB3SN)

Central field	13T @ 4.2K 15T @ 1.9K
Bore aperture	100 mm
Length	1.6 m
Outer Diameter	1.03 m
Weight	10.6 t



FRESCA 2 (NB3SN)





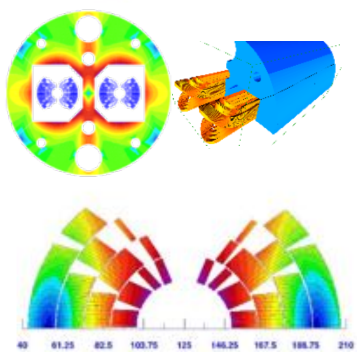
14.6T obtained in April 2018

MAGNET CONCEPTS FOR 16 T MAGNETS

Exploration of different magnetic designs

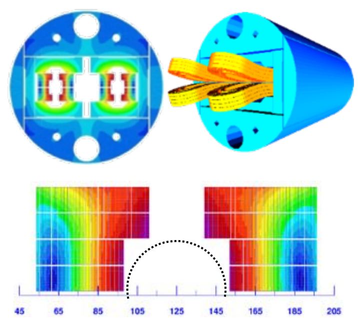
- Compact cost effective magnets
- Reliable series production
- Field quality
- Fast training magnets

INFN Istituto Nazionale di Fisica Nucleare



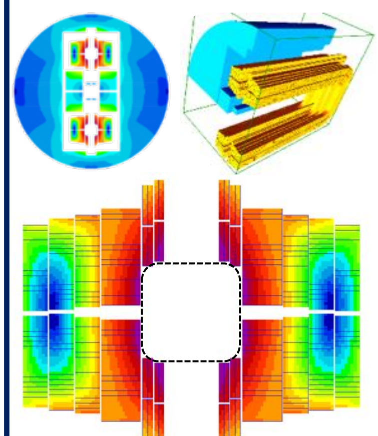
-Conductor amount
- Simple *Grading*
-Mechanical stress distribution

CEA



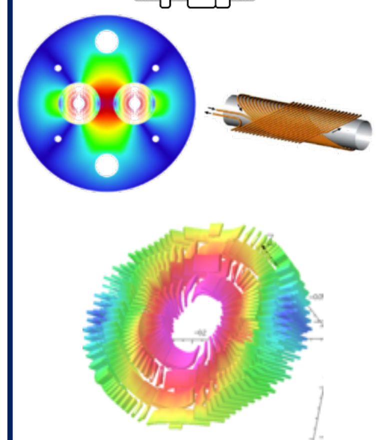
-Conductor amount
-Mechanical stress distribution
-Complex *Grading*

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



- Simple *racetrack coils*
-Amount of conductor
-Mechanical stress

PAUL SCHERRER INSTITUT PSI



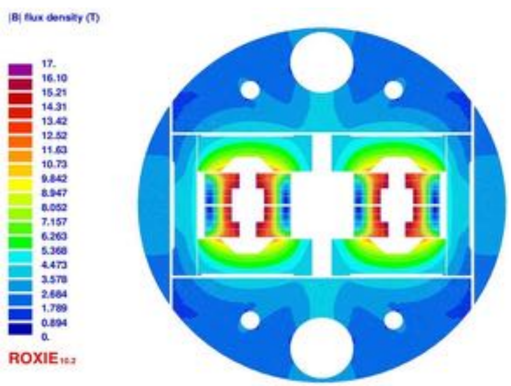
-Number of components
-Amount of conductor
- Number of interfaces

Courtesy of C. Lorin, CEA

DIPOLE BLOCK DESIGN FOR EUROCIRCOL

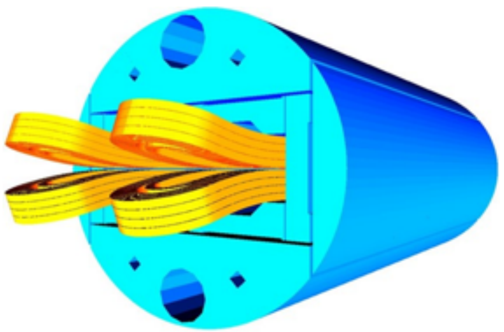
Within the ECC program => CEA Saclay in charge of the double aperture block-type configuration

2D magnetic model

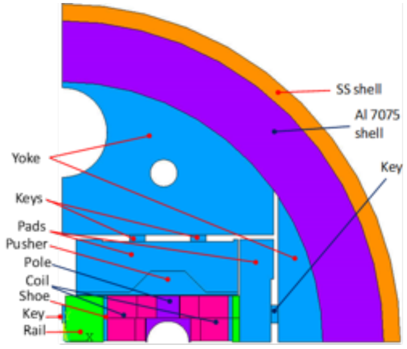


Aperture	50 mm
I_{op}	10176 A
LL margin HF	14.0 %
B_{bore}	16 T
B_{peak} HF	16.7 T
σ_x / σ_{VM}	
RT loading	-147 / 136 MPa
Cool-down	-180 / 165 MPa
Excitation	-185 / 167 MPa

3D magnetic model

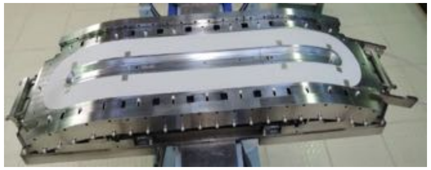


2D mechanical model



- Design Study ECC
- Manufacturing experience with FRESCA2

FRESCA2

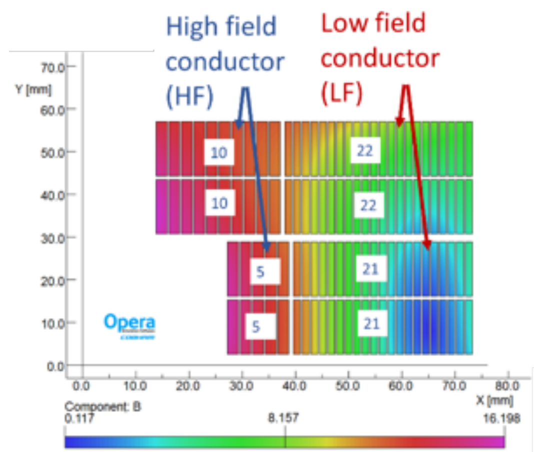


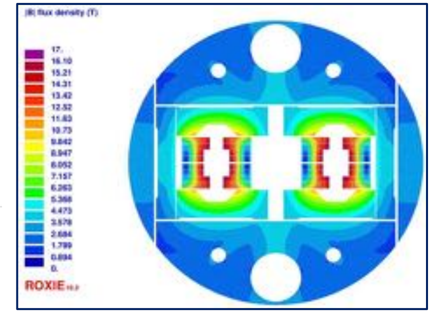
DIPOLE MODEL TOWARD FCC

CERN-CEA collaboration agreement to design and fabricate a single aperture block model at CEA

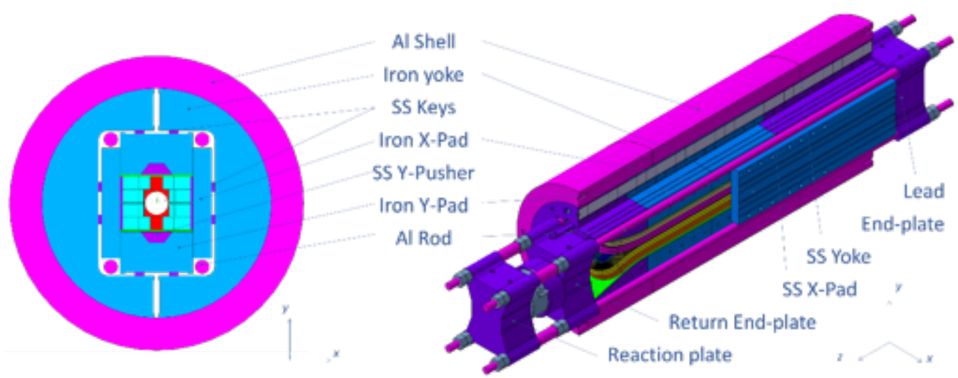
⇒ FCC Flared-ends Dipole Demonstrator: F2D2 => as close as possible to ECC

Conductor parameters	HF	LF
Strand diameter	1.1 mm	0.7 mm
Cu/nonCu ratio	0,8	2
Jc at 4.2 K and 16 T	1200 A/mm2	
Cable number of strands	21	34
Unreacted bare cable width	12.579 mm	
Unreacted bare cable thickness	1.969 mm	1.253 mm
HT cable thickness dim. change	4.6 %	4.5 %
HT cable width dim. change	1.3 %	
Reacted bare cable width	12.74 mm	
Reacted bare cable thickness	2.06 mm	1.31 mm
Insulation thickness at 50 MPa	0.150 mm	

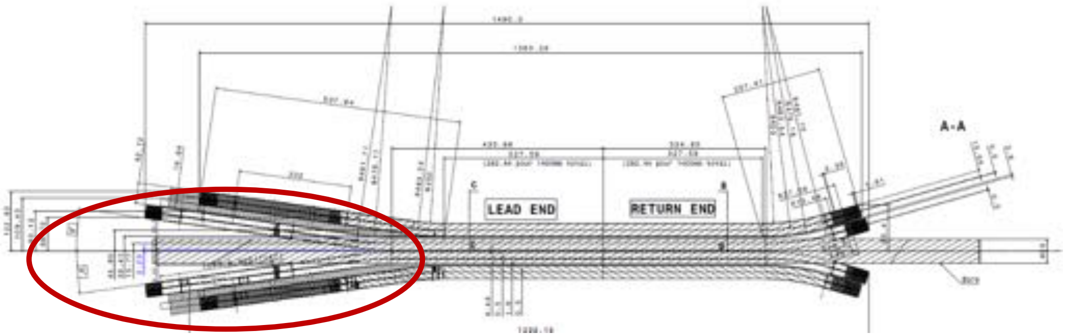


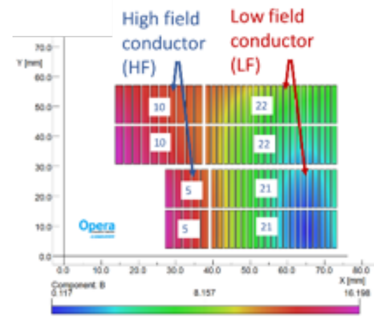


2D magnetic parameters	
I_{op}	10469 A
LL margin HF	14.0 %
LL margin LF	15.4%
B_{bore}	-15.54 T
B_{peak} HF	16.20 T
B_{peak} LF	11.85 T
b_3 at nominal	2.98
b_3 at injection	-14.80
b_5	-0.50
b_7	-2.98
b_9	-1.46

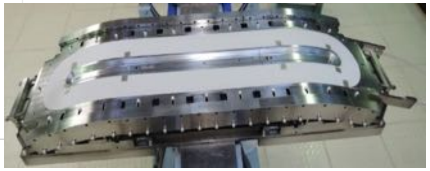


DIPOLE MODEL TOWARD FCC



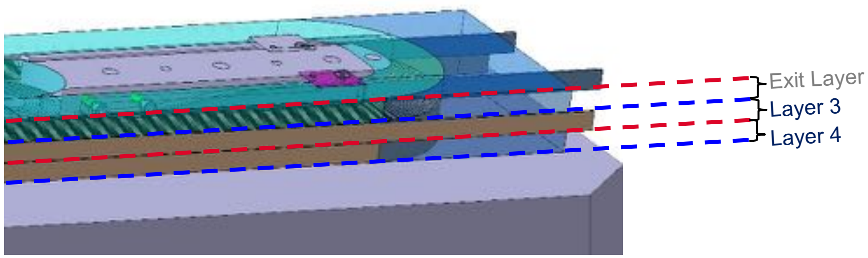


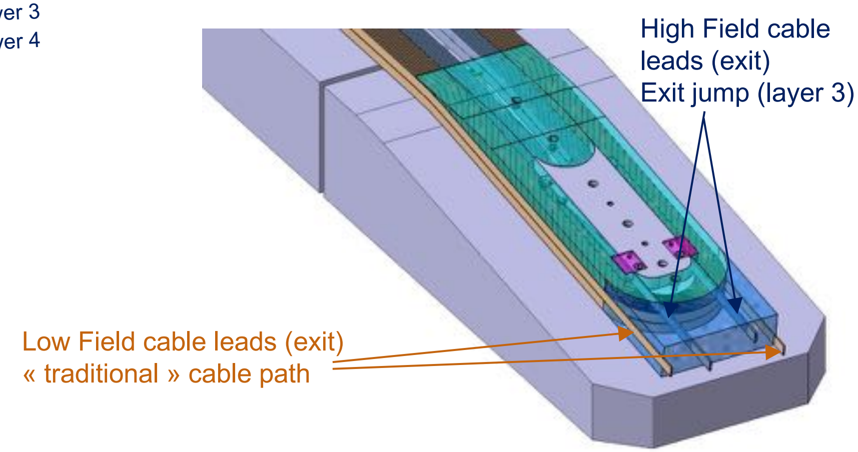
FRESCA2



Taking the leads out:
- Btw coil 1-2 and 3-1 for coil 3-4
- Toward the aperture for coil 1-2

- High complexity due to grading
- Baseline scenario: external joints





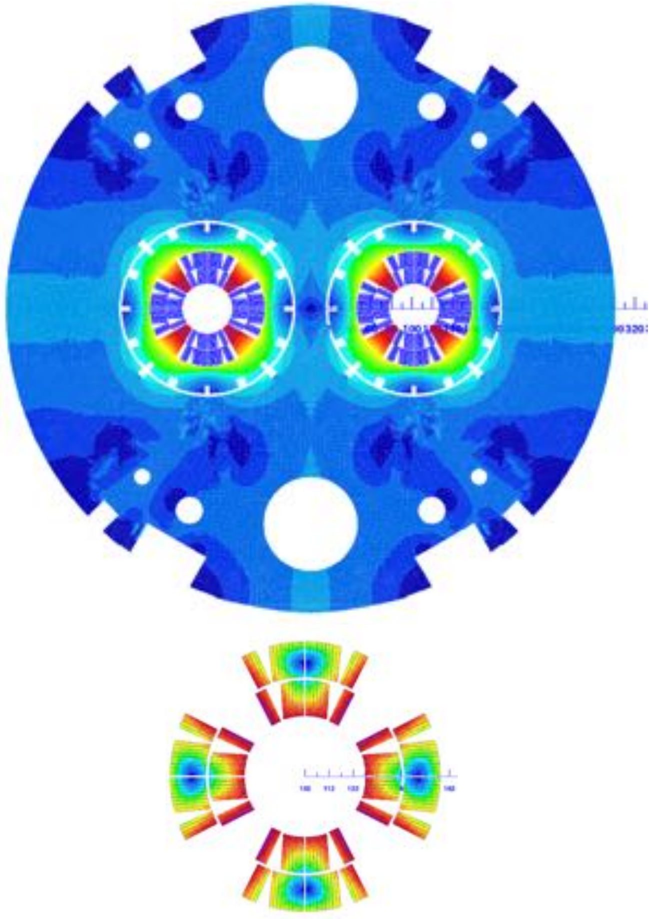
<u>Key challenge</u>: Coil and tooling engineering design
<u>Objectives</u>: manufacturing and assembly F2D2 at CEA

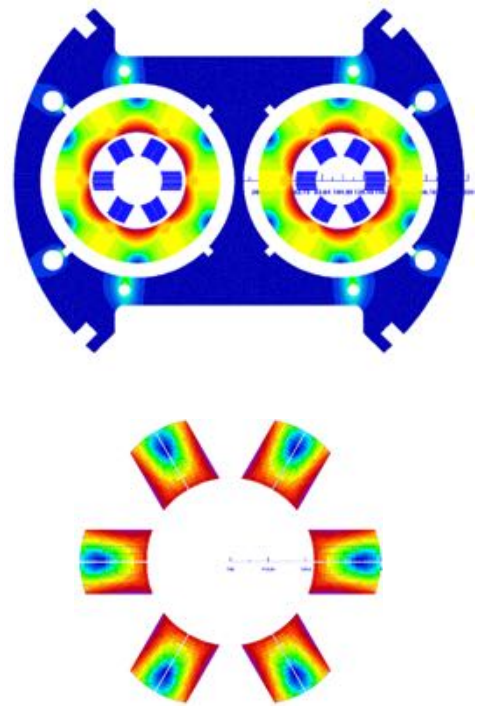
FCC MAIN QUADRUPOLE

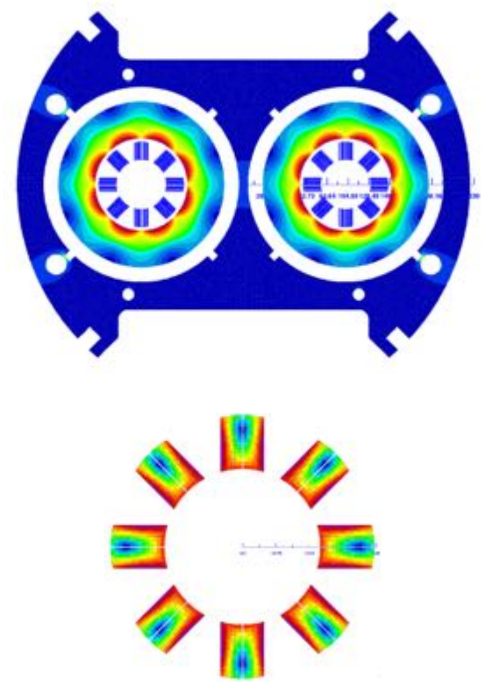
(MQ)

(MS)

(MO)







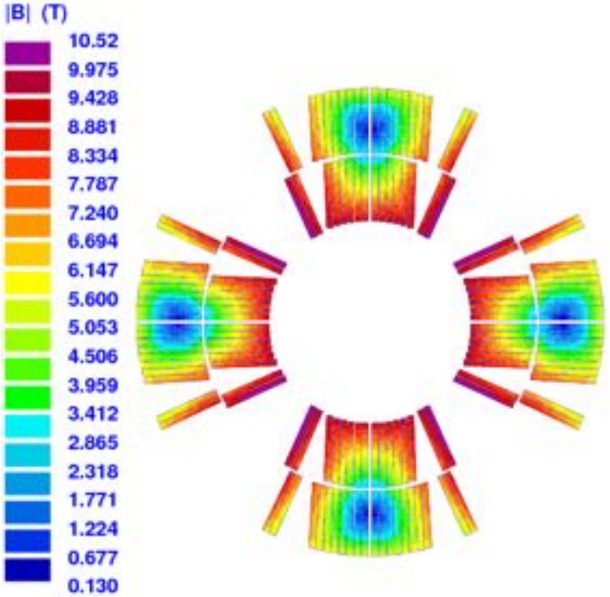
NB_3SN MAGNET TOWARD FCC MQ (I)

Within CERN-CEA collaboration

- In CEA tradition => design study of main quadrupole for FCC

- **Design study:**
  - 2 layer versus 4 layer designs ?
  - Margin of the quadrupoles?

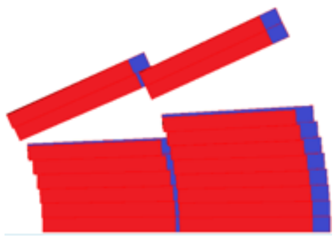
- Reduce complexity of the quad vs the dipoles => 2 layer quad
- 20 % margin (instead of 14 % for the dipoles)
- Nominal gradient above 360 T/m



- Conductor definition
  - Small aperture => cable windability is a concern

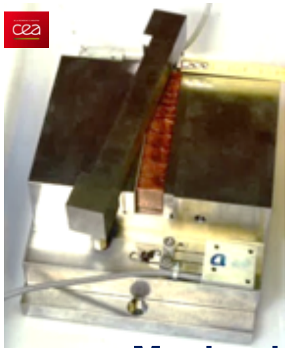
CABLE PARAMETER	FCC quad (v12)
Strand diameter	0.85 mm
Cu/NonCu	1.65
Nb of strands	35
Cable bare width (before/after HT)	15.956/16.120 mm
Cable bare mid-thick.(before/after HT)	1.493/1.538 mm
Cable width expansion	1.0 % (ECC)
Cable thickness expansion	3.0 % (ECC)
Keystone	0.40°
Insulation thickness per side (5 MPa)	0. 150 mm

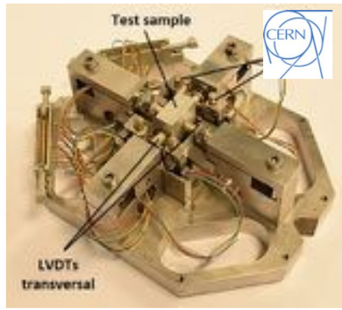
Cable validation
Winding test with
MQXF cable

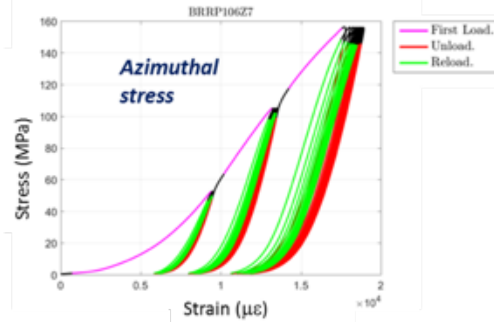


MAGNET PARAMETER	Values
Nominal current	22500 A
Peak field	10.52 T
Gradient	367 T/m
Loadline margin	20.0 %
Temperature margin	4.6 K

MAGNET TECHNOLOGY DEVELOPMENT: A NON EXHAUSTIVE LIST



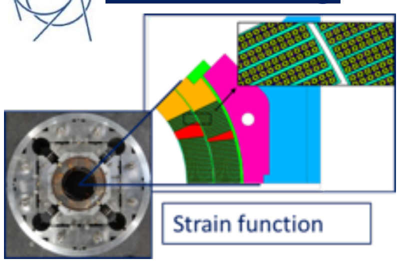


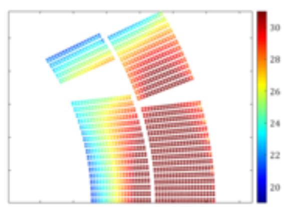


Mechanical behavior characterization of Epoxy impregnated Nb_3Sn => complex non linear orthotropic behavior

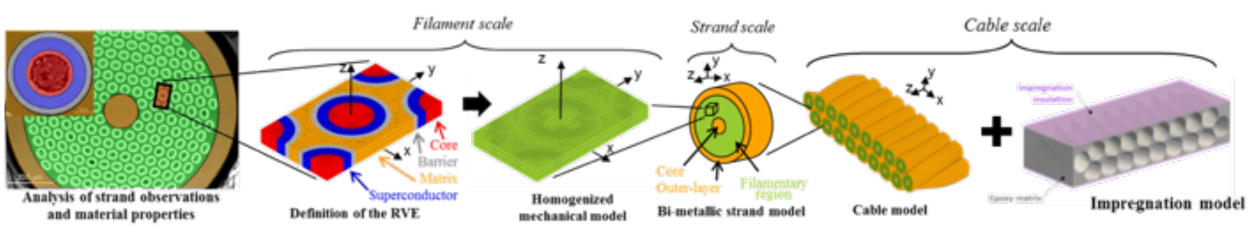
Conductor dimensional changes during heat treatment

Modeling => accounting for Ic reduction in magnet design





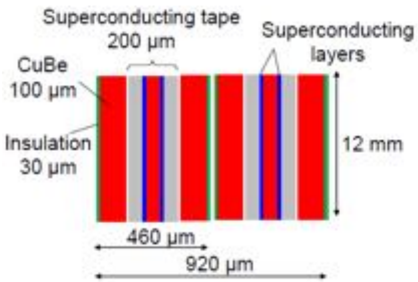
Ic reduction map
through strain function
Multiscale approach

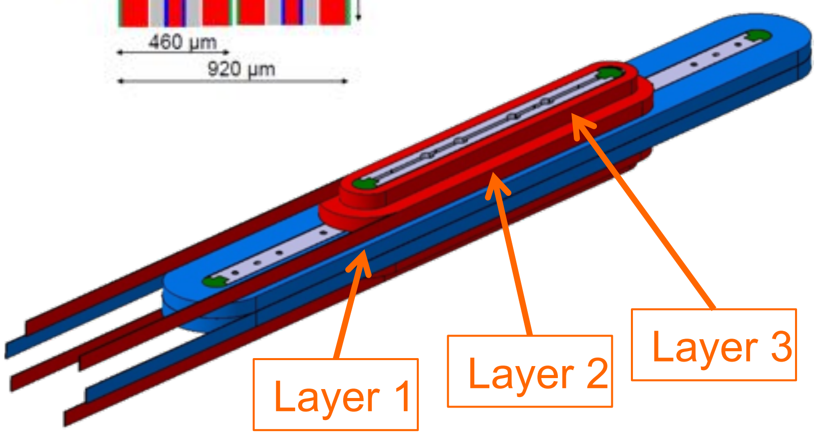


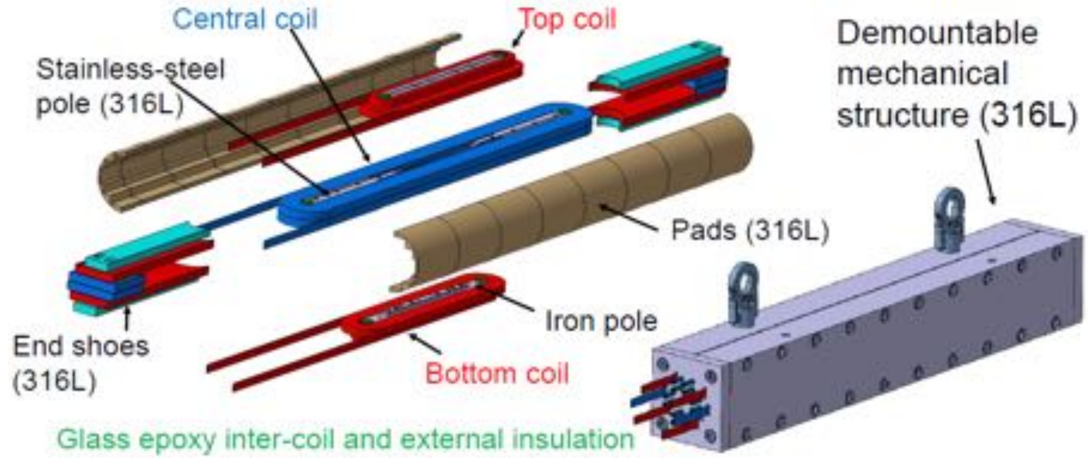
Courtesy of BM. Durante (CEA),C. Fichera (CERN)

TOWARD HTS ACCELERATOR MAGNETS: EUCARD

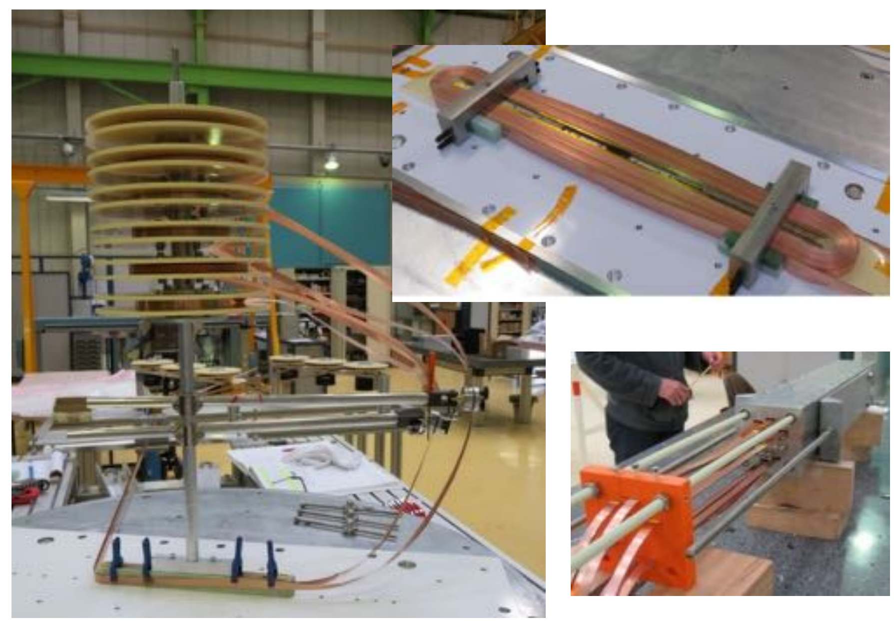
6 co-wound tapes: 2 SC + 4 CuBe





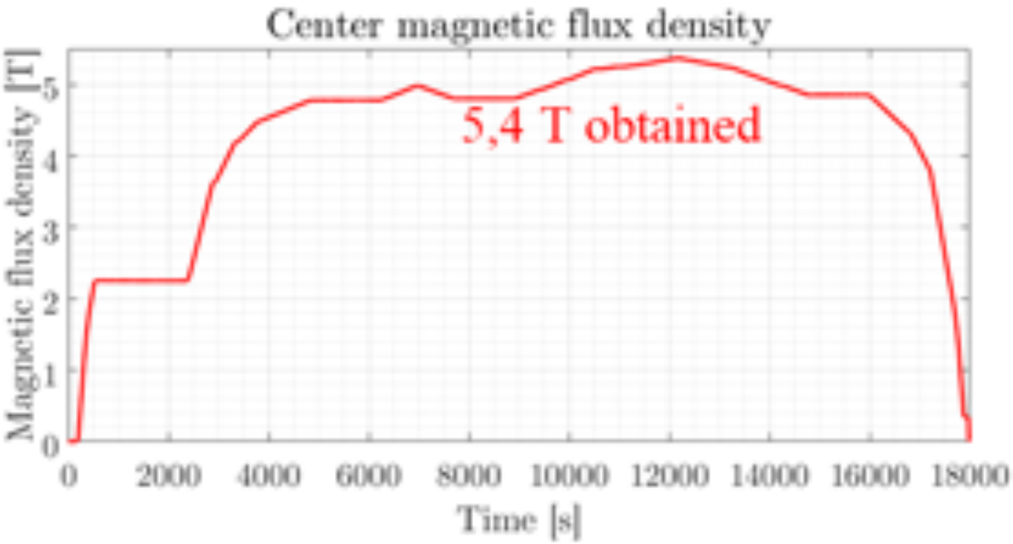


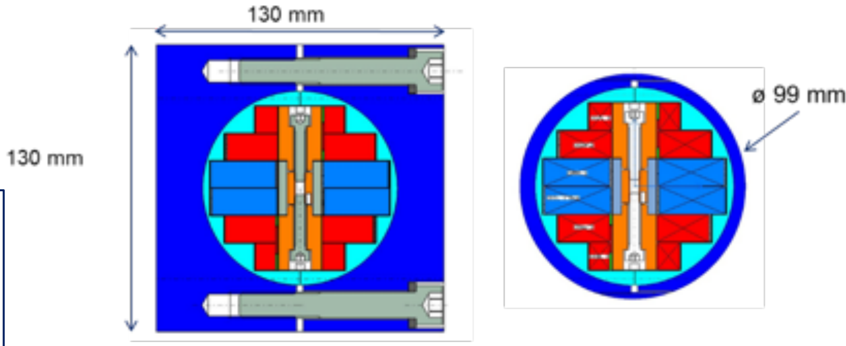
PARAMETER	Built Magnet	Unit
# of turns central coil layer 1	30	turns
# of turns external coils layer 2	24	turns
# of turns external coils layer 3	10	turns
Engineering current density	235	A/mm^2



TOWARD HTS ACCELERATOR MAGNETS: EUCARD

Nominal current	A	2800
Central field wo / w SCIF (screening current induced field)	T	5.4 / 4.7
Temperature	K	4.2
Stocked energy	kJ	12.5
Inductance	mH	3.2
Temperature margin	K	29
Load line margin	%	47





Phase 1

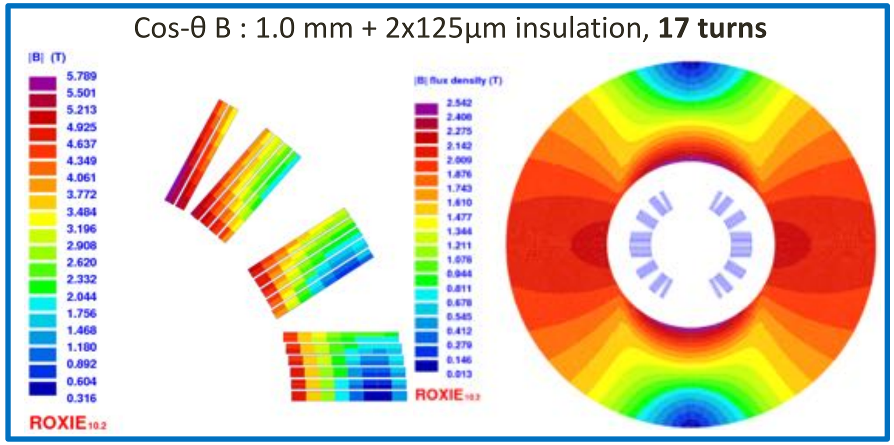
Phase 2

- Tested at CEA Paris Saclay and reached 5.4 T
- Next step: insertion of EUCARD in FRESCA2
  - Preparation is ongoing

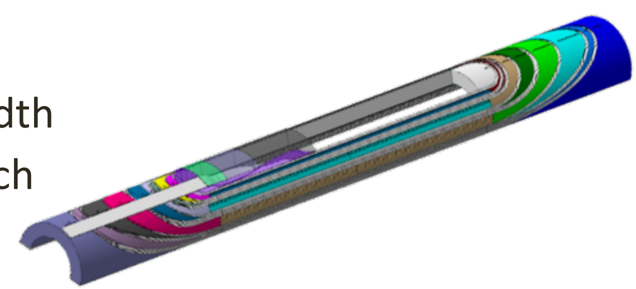
EUCARD2 COS-ϴ - STANDALONE

Design B - « thin » cable : 12 x 1.0 mm² bare, 15 tapes 100 µm-thick

Layout	Unit	Cosϑ B
Iop	kA	10.06
Bop	T	**5**
Bpeak	T	5.8
Ic	kA	15.2
LL margin	(%)	34
T margin	K	30
Sd. inductance	mH/m	0.73
coil inner radius	mm	**24**
yoke inner raidus	mm	50
yoke outer raidus	mm	110
Nb. of turns	-	17
Unit len. of cond.	m	24



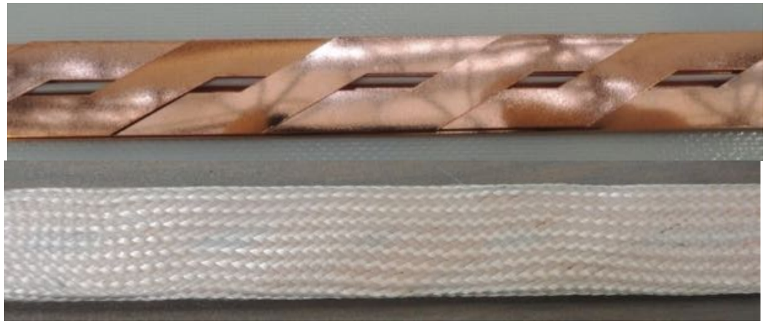
- EuCARD2 Roebel « thin » cable :
  - 12 x 1.0 mm²
  - 15 tapes 100 µm
  - 12.0 mm total width
  - 300 mm twist pitch



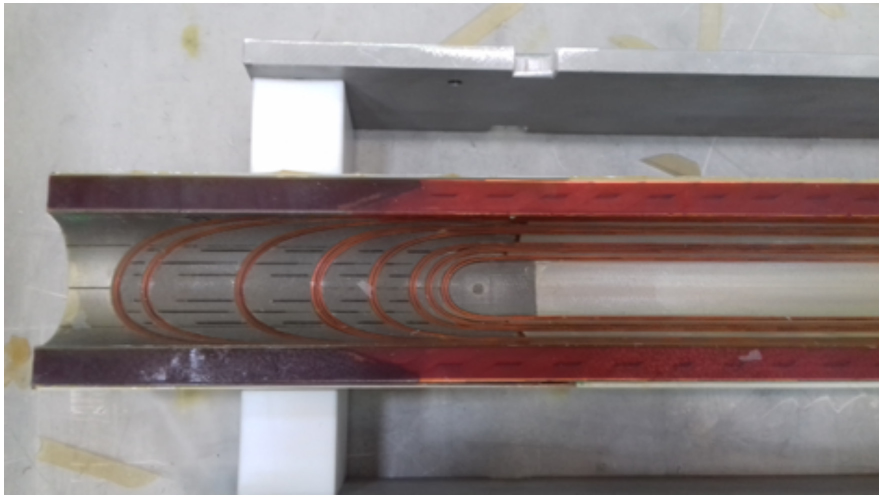
- 2x125µm insulation

EUCARD2 COS-Θ - MANUFACTURING

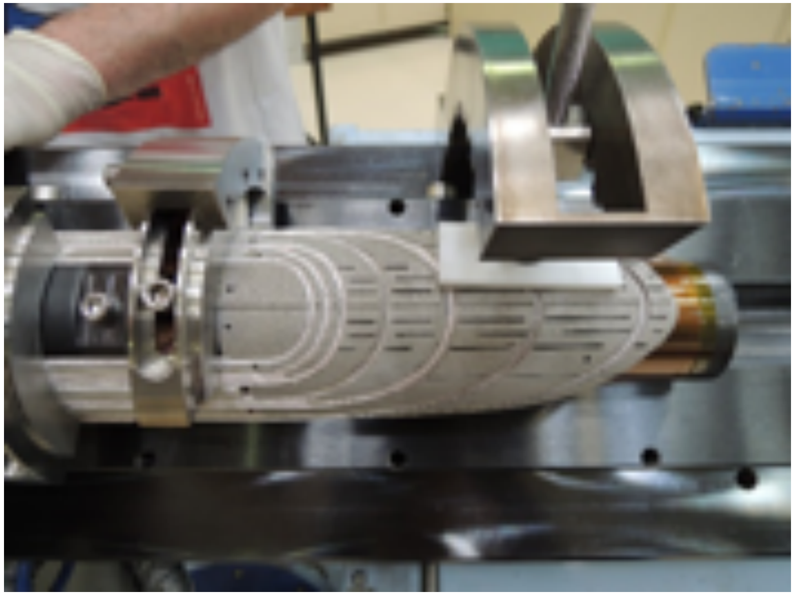
Insulated SuperOX Roebel cable



First coil Summer 2019



Coil winding



Second coil Fall 2019

- **Tests scheduled next year at INFN Lasa**

ACCLERATOR MAGNET PERSPECTIVES

- Encouraging 13-14^{+} T Nb_3Sn short model results (Fresca 2)
- Focused on 14-16 T design and model development for FCC dipole and quadrupole

The community is working

- as an international team
- with a consistent development program

to tackle the remaining Nb_3Sn challenges

We are on a consistent path toward the 14-16 T (nominal) frontier

Encouraging results using HTS accelerator dipole inserts
but still a lot to do and
it will be a long long way to a fully operational 20 + T HTS accelerator magnet

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DACM

Some examples…

- Magnets for Accelerators
- **Magnets for Detectors**
- High field magnets
- MRI magnets

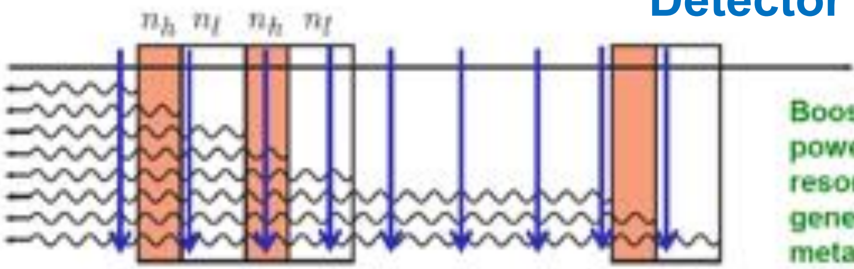
MADMAX

Axion to photon conversion at sufaces:

Many surfaces → resonator → "photon boost"

J. Jaeckel and J. Redondo, Phys. Rev. D 88 (2013) 115002 [arXiv:]

Detector for Max Planck Institute for Physics (MPP)



Boost factor:
power generated in resonator/power generated on single metallic ($\varepsilon_r = \infty$) surface

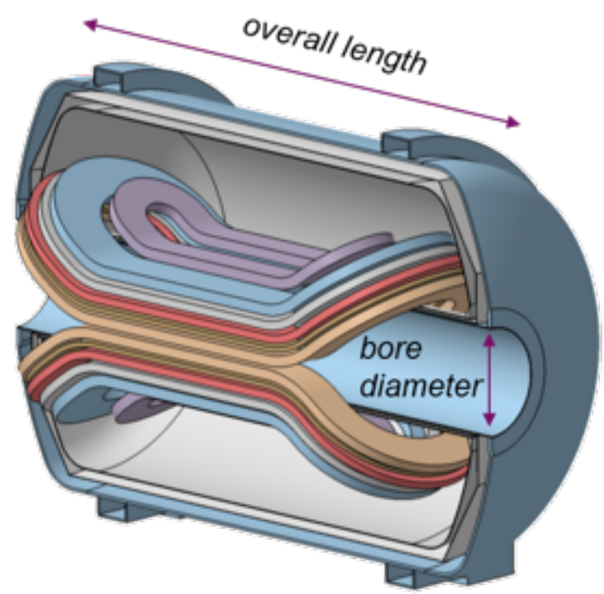
$$(P/A)_{resonant\ cavity} \sim 2 \cdot 10^{-27}\ W/m^2 \cdot (B_{\|}/10T)^2 \cdot c_\gamma^{\ 2} \cdot f(\varepsilon_{m1}, \varepsilon_{m2}) \cdot \beta$$

β : Boost factor, depends on:
frequency (axion mass), ε of materials, number of surfaces, displacement between surfaces, etc.

- NbTi Conductor
- Superfluid helium cooling

Design Constrains	
Bore Diameter	1250 mm
Overall Length	< 6900 mm
Magnet Length	< 5900 mm
Overall Mass	200 tons
B peak (10% LL @ 1.8 K)	< 12 T

Specification	
FoM (Z = 0 mm)	100 T²m²
FoM (Z = ±1000 mm)	> 90 T²m²
B Field Homogeneity (H)	± 5%



Some examples…

- Magnets for Accelerators
- Magnets for Detectors
- **High field magnets**
- MRI magnets

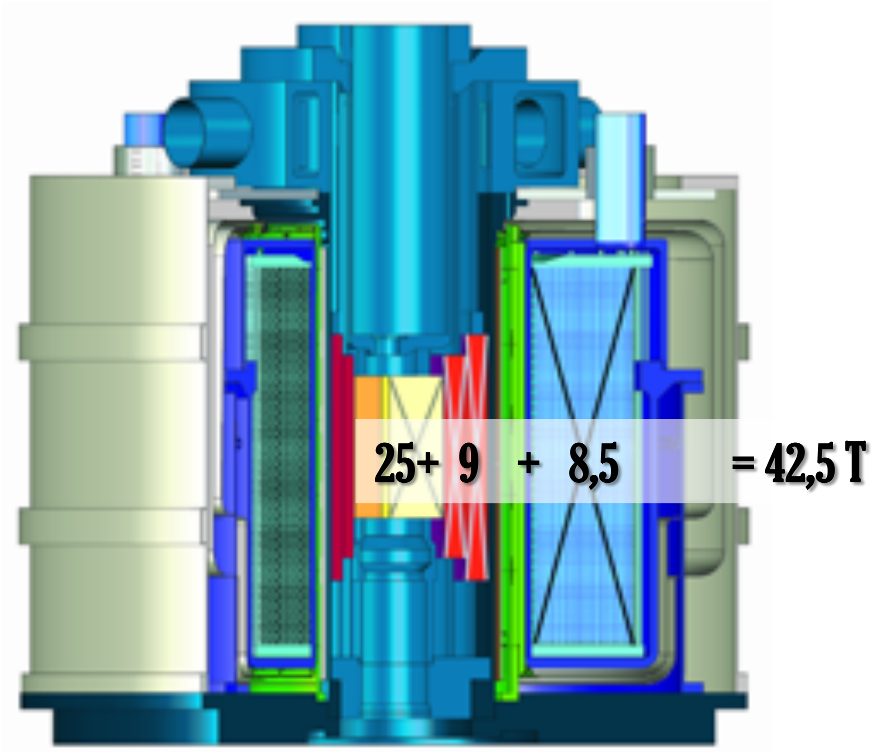
HIGH FIELD HYBRID MAGNET LNCMI-GRENOBLE

Objective: Exceed 42 teslas in the LNCMI Grenoble Hybrid Station

The CEA is involved in the studies and realization of the superconducting magnet outsert, the cryogenic satellite and the heat pipe.

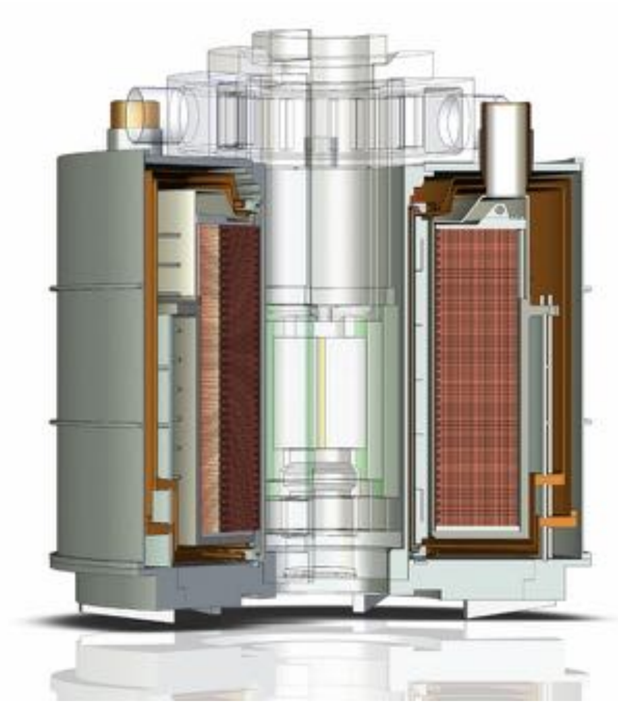
CNRS LNCMI is prime contractor for the hybrid station.

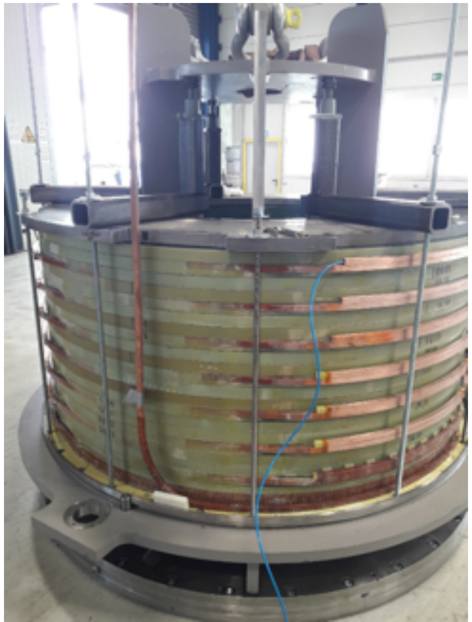
- Superconducting magnet alone 8,5 T
  - 8,5 T ■ Φ 800 mm ■ (700 kW)
- Supercond. + Bitter (9 T)
  - 17,5 T ■ Φ 376 mm ■ (12 MW)
- Supercond. + Bitter + Polyhelix (25 T)
  - 42,5 T ■ Φ 34 mm ■ (24 MW)



HIGH FIELD HYBRID MAGNET LNCMI-GRENOBLE

- B 8.5 T
- T_{op} 1.8 K
- R_{int} bobine 550 mm
- R_{ext} bobine 913 mm
- Hauteur 1400 mm
- Masse bobine 17 t
- Courant 7100 A
- Inductance 3 H
- E stockée 76 MJ





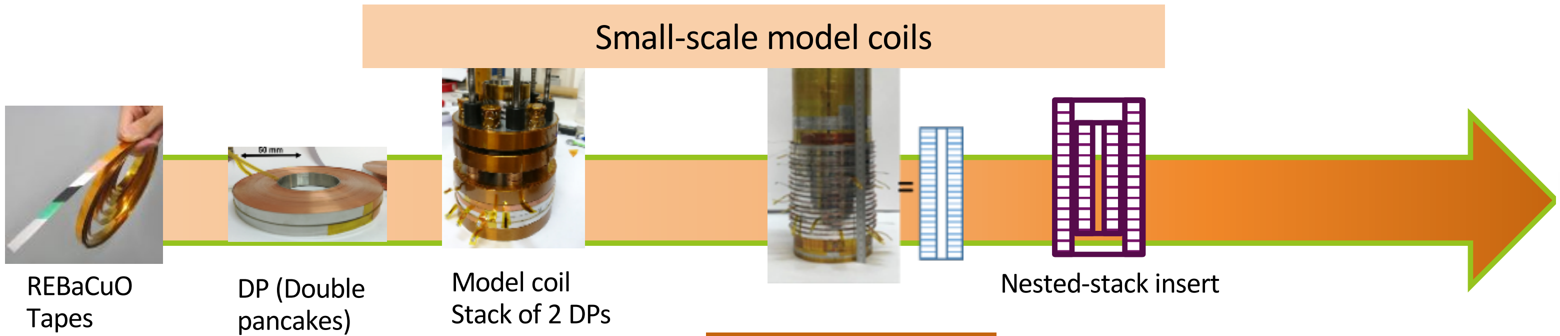
Magnet manufacturing
(BNG, Allemagne)

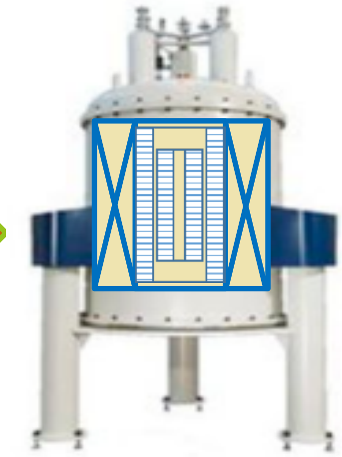
Operation in 2021

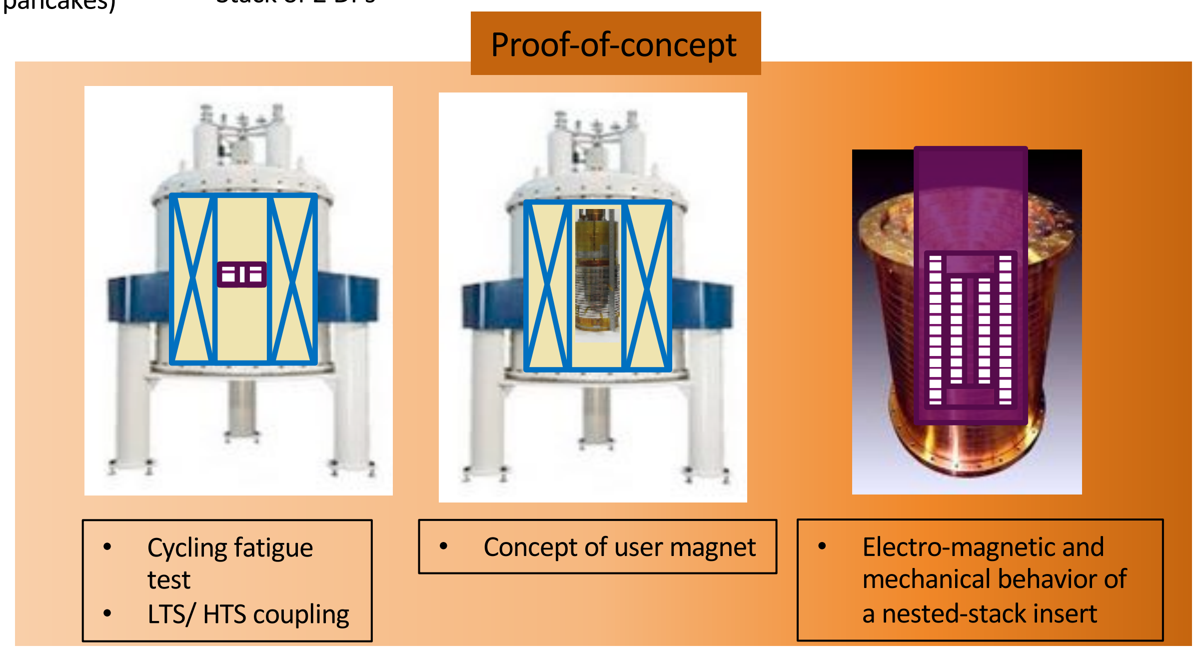
Assembly of the cryogenic satellite LNCMI

NEXT STEP : SUPEREMFL

From tapes to a full SC 40 T + magnet chart







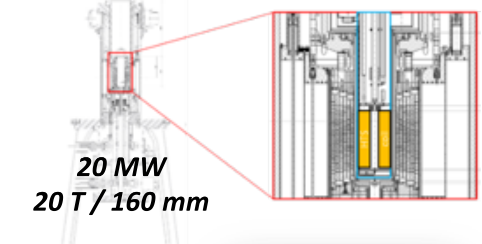
Target :
Conceptual design of a 40 T+ magnet

Byproducts :
Dedicated intermediate field magnets

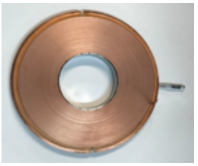
FULLY SUPERCONDUCTING MAGNET

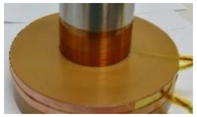
GOAL: 10 T HTS INSERT IN 20 T RESISTIVE OUTSERT

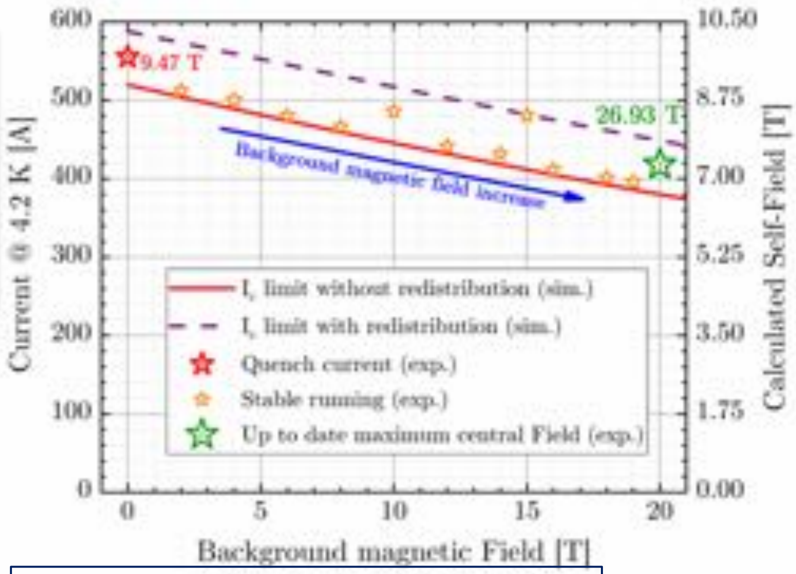
- 4 years project (oct 2014 -2018)
- Fundings from French National Research Agency (lead LNCMI)
- Collaborative project with CNRS Grenoble (LNCMI, Neel institute)



- Double pancakes, 6 mm-w ReBCO
- Metal-as-Insulation winding
- Prototypes (1 SP, 2 DP), codes (current dynamics…)
- 9 DP, ~ 2 kms of conductors







2 DP proto tests

***6.93 T** + 20 T res*

VonMises> 800 MPa

Validation of fabrication, assembly and testing techniques and mechanics

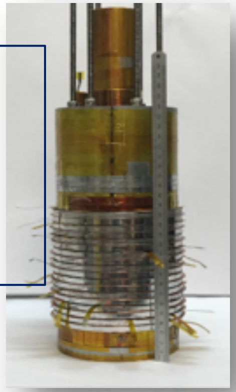
NOUGAT insert tests (9DP)

First phase (2018)

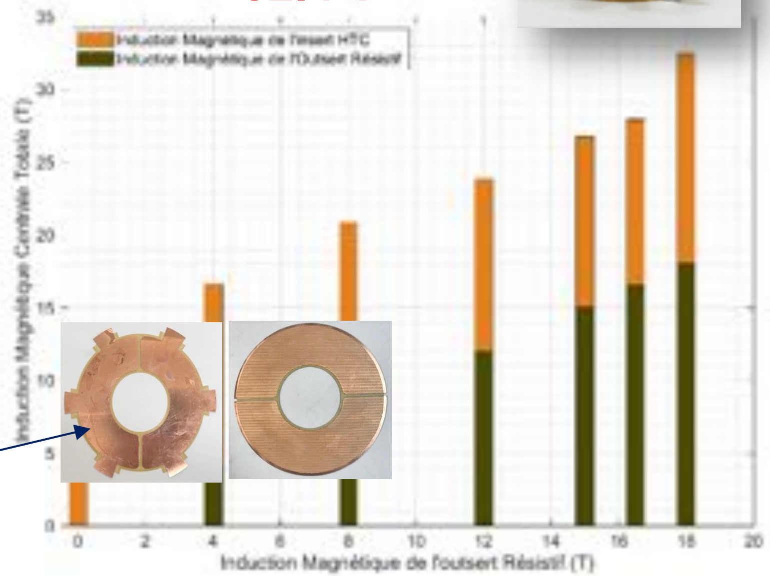
***12.8 T** + 8 T res*

Second phase (2019)

***@14.5 T+18 T res** VM # 500 MPa*



32.4 T



Improved cooling

HTS HIGH FIELD R&D OVERVIEW

Detection/Protection

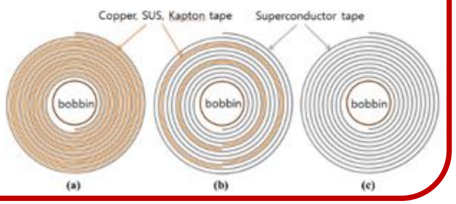
Detection difficult due to very low propagation velocities during a quench.
Protection not easy due to very high energy margin (high Tc)

- *Numeric Magnet Safety System*, more accurate and faster (FPGA)

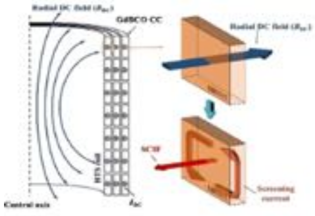
Remove/replace insulation between turns :

- *NOUGAT project*
  # HTS insert HTS with Metal-as-insulation winding

- *Internal R&D "No Insulation-Partial Insulation –Metal-as-Insulation"*
  # study of stability/protection/ time constants of different windings



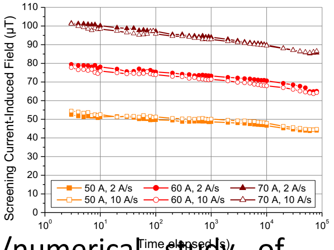
Stability/Homogeneity



Degradation of stability/homogeneity due to screening currents generation

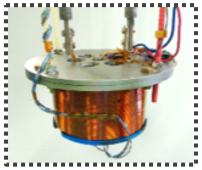
- *Guillaume Dilasser PhD*

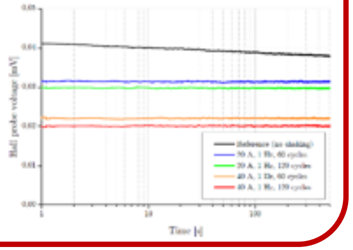
Experimental and numerical studies of screening currents in REBCO tapes



- *Internal R&D*

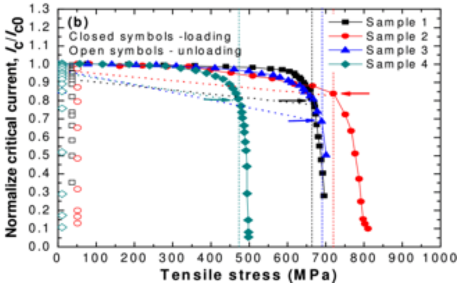
experimental/numerical study of different techniques (overshoot, vortex shaking)





Mechanics

Issue for very high-field magnets
(> 30 T)
Ex : JBr > 1000 MPa
J=500 A/mm², B = 40 T, r=5 cm



- *MI winding* co-wound tape is a strong mechanical reinforcement

- *M. ALHarake PhD* : mechanical study of non impregnated windings at very high fields

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Institut de recherche sur les lois fondamentales de l'Univers

DACM

Some examples…

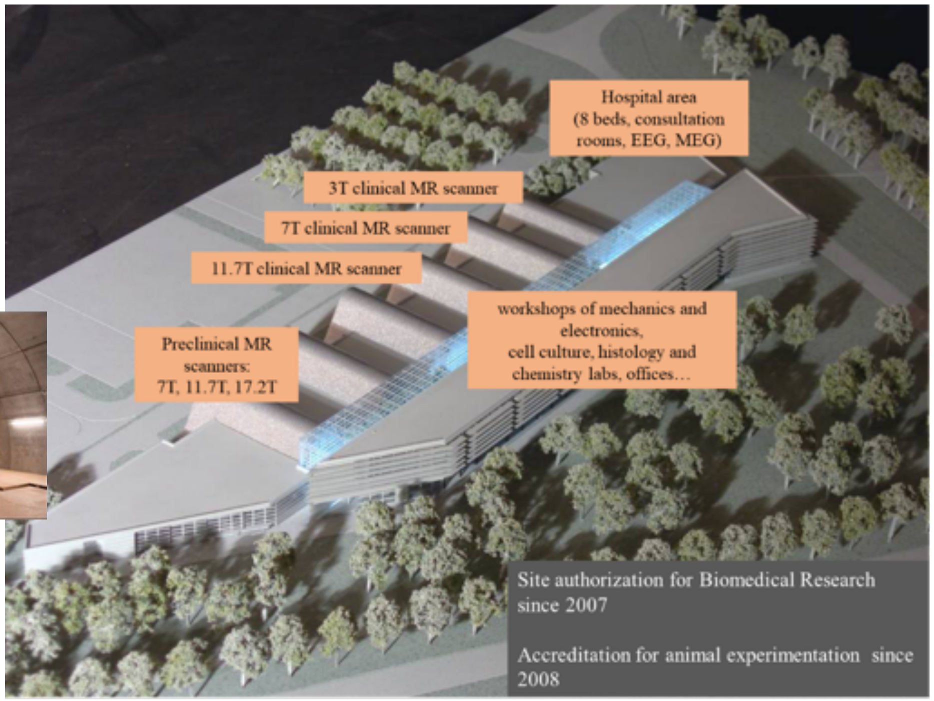
- Magnets for Accelerators
- Magnets for Detectors
- High field magnets
- **MRI magnets**

NEUROSPIN
A UNIQUE FACILITY FOR NEUROSCIENCE RESEARCH

3 teslas Siemens

7 teslas Siemens

11,7 teslas



Neurospin was opened at CEA Saclay in 2007
Facility equipped with several commercial MRI systems

THE ISEULT MAGNET

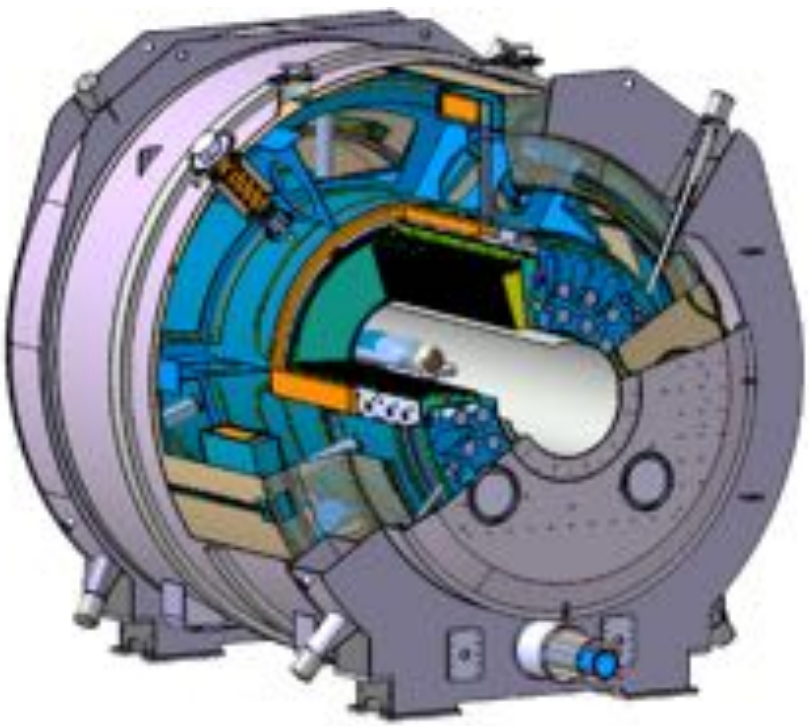
A very tight specification:

- **B0 / Aperture 11.72T (500 MHz for proton resonance)**
- **Aperture 900mm**
- **Field stability 0.05 ppm/h**
- **Homogeneity < 0.5 ppm on 22 cm DSV**
- **Stray field 5 G : 13.5 m axial, 10.5 m radial**

Innovative solutions for a MRI magnet

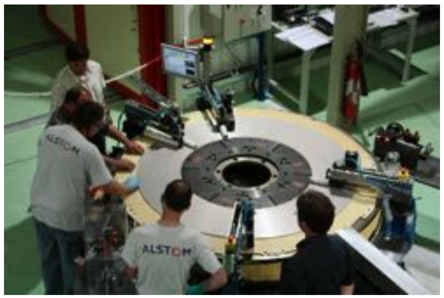
- **170 NbTi double pancakes** for the main coil
- **2 NbTi shielding coils** to reduce the fringe field
- Cryostat for **superfluid helium at 1.8 K**, 1.25 bars
- **Dedicated cryorefrigerator (**80 l/h + 40 W @ 4.2 K)
- **Driven mode operation**, with two 1500 A power supplies

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Length	5.2 m
Diameter	5 m
Weight	132 t

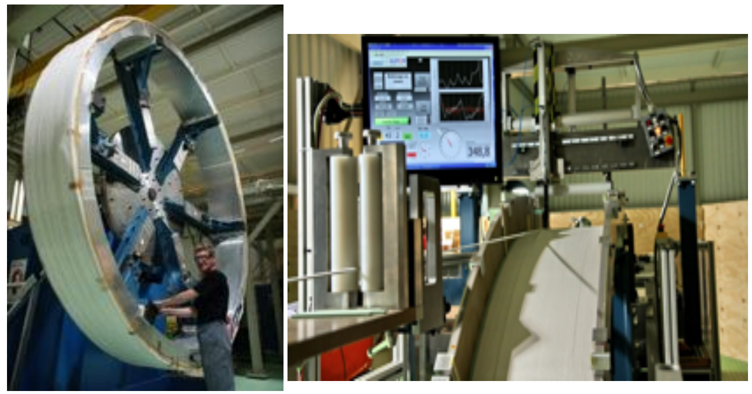


11.7 T magnet section : in orange the windings, in blue the mechanical structure at 1.8 K and in violet the cryostat

MAGNET MANUFACTURING
ALSTOM (GE) BELFORT (2010 – 2017)

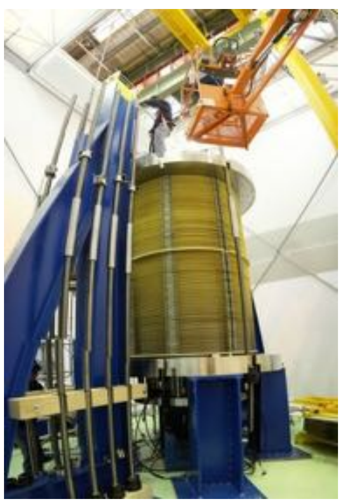


Double pancake manufacturing



Shielding coil manufacturing

Coil integration



170 double pancake stacking

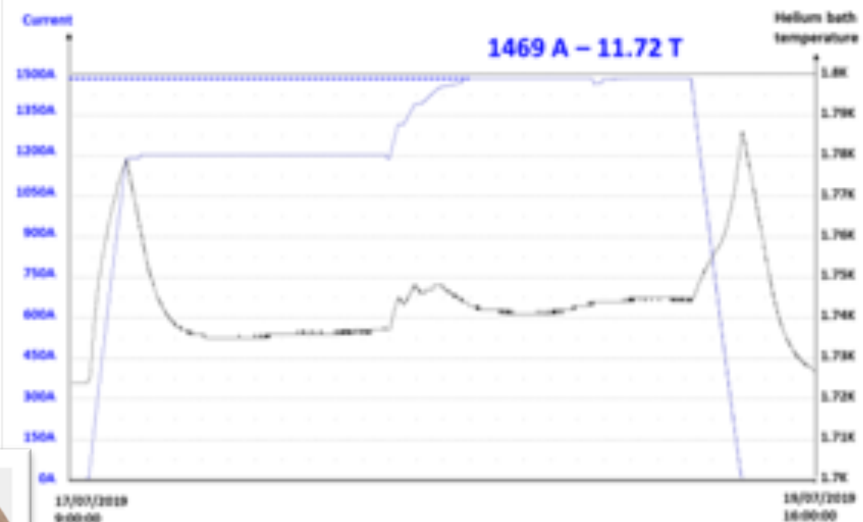
MLI assembly

Cryostat assembly

STEP BY STEP ENERGIZATION 11.72T – 18 JULY 2019

2 days of tests:

- **Current ramp up in 30 hours**
- **First magnetic measurements (spatial homogeneity and temporal stability)**
- **Slow discharge to lower the current**



HIGH FIELD MRI LANDSCAPE

2001
- 3T : ≈ 100 systems
- 2 systems 7T Whole Body (WB)
- 1 systems 8T WB

2019
- 7T : ~ 100 systems -– 6 to 10 new units per year

- 1 system 8T WB: Ohio State Univ (80cm)

- 6 systems 9.4T WB: Minneapolis (65cm), Chicago (80cm), Tübingen (82cm), Jülich (90cm), Maastricht (82cm), Beijing (83cm)

- 1 system 10,5T WB: Minneapolis – 88cm – Passive shielding, humain brain images since 2018

- 3 projects WB 11.7T:
- **- Iseult: 90cm/active shielding, NIH/Bethesda: 68cm/passive shielding,**
- **-NRI (Séoul): 68cm/passive shielding**

Future projects @ 14T : USA (Boston, Stanford), Chine (Beijing, Shenzhen)

FUTURE R&D FOR MRI MAGNETS

MRI magnet

low field

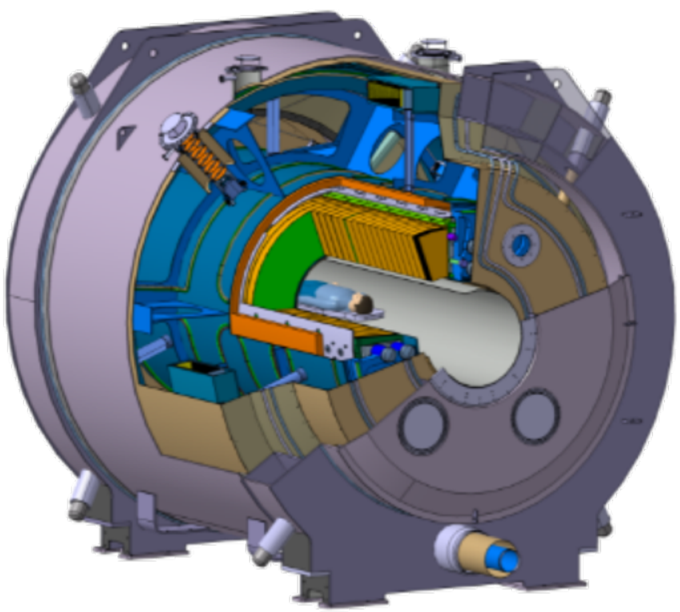
HTS

1- 3 T

Cryogen free

Low electrical consumption

Worldwide collaborations
with academics and industries
to develop MRI magnets for the future



MRI magnet

high field

Nb_3Sn

> 14 T

Whole body

R&D Nb_3Sn

HTS > 16 T







Thank you for your attention !